

Performance assessment of EIT measurement systems

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Abstract. EIT acquisition systems, when regarded as measuring instruments, can be characterized by their inherent characteristics: reproducibility, repeatability and discrimination. The ultimate limit to all three is noise, whether long-term or short-term noise. In addition, for some applications accuracy can also play a role, although accuracy is not an inherent characteristic and requires a known test object to be defined. Because EIT systems are multichannel instruments and the information of all channels is being combined to produce an image, a procedure to standardize the performance assessment must be set up in order to allow for meaningful comparison of different systems or different settings in the same system. We propose the use of three parameters defined long ago but scarcely used among EIT systems designers: SER (Systematic Error Ratio), NER (Noise Error Ratio) and RER (Reciprocity Error Ratio). We applied these definitions to our latest EIT instruments, TIE5-sys, in a wide frequency range and with different settings in configurable acquisition parameters and provide the interpretation of the results obtained in terms of reproducibility, repeatability and discrimination. We also comment on the tradeoffs that show up when using the usual definition for these figures.

1. Introduction

Measurement systems can be characterized by its inherent characteristics: discrimination, repeatability and reproducibility [1] which are related to the internal structure of the system and to noise. In addition, accuracy may also be interesting in some cases. However, in order to define the accuracy for most measurement system, an external test object of declared value (standard) must be used [1].

Electrical Impedance Tomography (EIT) acquisition systems are complex instruments that need to take several individual measurements in order to produce a frame or image. These individual measurements will differ from each other in several ways: the internal configuration of switches may be different, or the profile of applied currents or voltages, the points of application of voltage or current in the object may be different, the collection points may be different, the gains or integration time in the measurement chain may also be different; to cite the most common expected changes.

Because of the large number of possible combinations, and because different systems using different approaches will have different combinations, it is not practical to give all the comprehensive information of noise or accuracy for each possible individual measurement, especially if this information will be used to make comparisons between systems.

The problem of system characterization and comparison arose from the very beginning in the development of EIT. During the European Concerted Action on Impedance Tomography (CAIT) a set

of figures were proposed to solve this issue [2]. The definitions were never published in widely available format, and the available documents are plagued with typographic errors. We intend here to revise the figures, comment on their applicability and present the results of characterization of our recently developed EIT instrument.

2. Definition of figures of merit

We will start by explaining the CAIT approach [2] and comment on the implications of these choices. The CAIT approach originally intended to assess the noise performance and the accuracy.

2.1. Systematic errors

Systematic errors may have, at least, two different origins.

1. The individual measurement obtained with a particular combination of factors differs from what is expected. To assess these errors the Systematic Error Ratio (SER) is defined.
2. Two individual measurements, obtained with two different combination of factors, which must yield the same result (e.g. because of the reciprocity theorem) differ, irrespective of the fact that the actual value is close to the expected one. To assess these errors, the Reciprocity Error Ratio (RER) is defined.

2.1.1. *Systematic Error Ratio (SER)*. SER is formally defined in equation 1. It is clear that in order to calculate this error, a known test object must be used. The test object can be built using components with an uncertainty smaller than the expected for the system, or might have been characterized using an instrument with a suitable uncertainty. In both cases, one must make sure that drifts are under control. For a frame of K individual measurements, with index k :

$$SER = \sqrt{\frac{1}{K} \sum_{k=1}^K \frac{(V_{mk} - V_{ck})^2}{V_{ck}^2}} \quad (1)$$

where: V_{mk} is the measured value for the measurement of index k
 V_{ck} is the theoretical value for the measurement of index k

If random errors are known to have values similar to that of expected SER, then it is advisable to use an average value instead of a single V_{mk} :

$$\bar{V}_{mk} = \frac{1}{N} \sum_{i=1}^N (V_{mk})_i \quad (2)$$

where N has an arbitrary value, large enough to make sure that the remaining random effect will not interfere with the calculation of SER.

2.1.2. *Reciprocity Error Ratio (RER)*. RER is formally defined in equation 3. It is clear that in order to calculate this error, no known test object is needed. The only restriction is temporal stability during the time required to acquire a frame. For a frame of K individual independent measurements, with index k :

$$RER = \sqrt{\frac{1}{K} \sum_{k=1}^K \left(\frac{V_{k,ij}^{ab} - V_{ab}^{ij}}{V_{k,ij}^{ab}} \right)^2} \quad (3)$$

where: V_{ij}^{ab} is the measurement obtained when applying current through electrodes i, j and detecting voltage through electrodes a, b .

Calculation of RER makes only sense for those systems that perform (or are able to) measurements that can be related using the reciprocity theorem. One particular case are systems using adjacent

injection and adjacent voltage detection. For that case, if a number of E electrodes are being used, there are $E(E-1)/2$ independent measurements, of which E measurements are three-wire measurements that tend to be saturated, so are not used in practice. This leaves $E(E-3)/2$ useful measurements. In order to calculate RER we need to make twice the number of measurements and acquire the reciprocal of the independent ones. In that particular case, and assuming that measurements are identified by two indexes i, j indicating the injection and detection pair, RER can be expressed as:

$$RER = \sqrt{\frac{2}{E(E-3)} \left[\left(\sum_{i=1}^{E-2} \sum_{j=i+2}^E \left(\frac{V_{ij} - V_{ji}}{V_{ij}} \right)^2 \right) - \left(\frac{V_{1E} - V_{E1}}{V_{1E}} \right)^2 \right]} \quad (4)$$

2.2. Random errors

Short term random errors are associated with noise, either from the current source or the voltage detectors. Depending on the dominant source of error and the architecture of the system, the combined effects of the different contributions will have different correlation coefficients. It is not always easy to estimate these correlation coefficients. No known test object is required to make the calculation of noise power. For an individual measurement of index k , the RMS value of noise, relative to the measured value, is called the Noise Error Ratio (NER) (which is the inverse of the Signal to Noise Ratio (SNR)). NER for an individual measurement V_k can be obtained as:

$$NER_k = \frac{1}{V_k} \sqrt{\frac{\sum_{i=1}^N (V_{ki} - \bar{V}_k)^2}{N}} \quad (5)$$

where N has an arbitrary value, large enough to make sure that the calculation is relevant. In order to give a single figure for the system, NER_k can be averaged, either linearly or RMS:

$$NER_L = \frac{1}{K} \sum_{k=1}^K NER_k \quad NER_{RMS} = \sqrt{\frac{1}{K} \sum_{k=1}^K NER_k^2} \quad (6)$$

NER_L was used within the CAIT, but NER_{RMS} is more consistent with the given definitions for SER and RER.

3. Characterization of TIE5_sys

The definitions on section 2 were used to derive figures of merit for our most recent system, TIE5_sys [3]. Because of TIE5_sys is a broadband system, all the above parameters were obtained for several frequencies within the frequency range of operation (10 kHz – 1 MHz). All the measurements were performed in a resistor-mesh phantom, known as CARDIFF EIT PHANTOM (v1.0 1991) [3] made of $100 \Omega \pm 1\%$ SMD resistors. The shape of the phantom is depicted in figure 1. Table 1 summarizes some of the results, obtained using a fixed (maximum) gain for the Programmable Gain Amplifier (PGA), common mode feedback (CMF) connected and no electrode impedances. Actual theoretical values for the test object were measured using an HP4192A Impedance Analyzer.

Table 1. Summary of results for SER, RER and NER_L as a function of frequency for TIE5_sys

	10 kHz	30 kHz	50 kHz	80 kHz	100 kHz	300 kHz	500 kHz	700 kHz	1 MHz
SER (%)	0.49	0.44	0.46	0.51	0.59	1.87	5.28	9.81	17.53
RER (%)	0.74	0.73	0.66	0.63	0.63	0.81	2.38	5.29	4.91
NER_L (%)	0.048	0.033	0.035	0.029	0.032	0.031	0.031	0.031	0.029

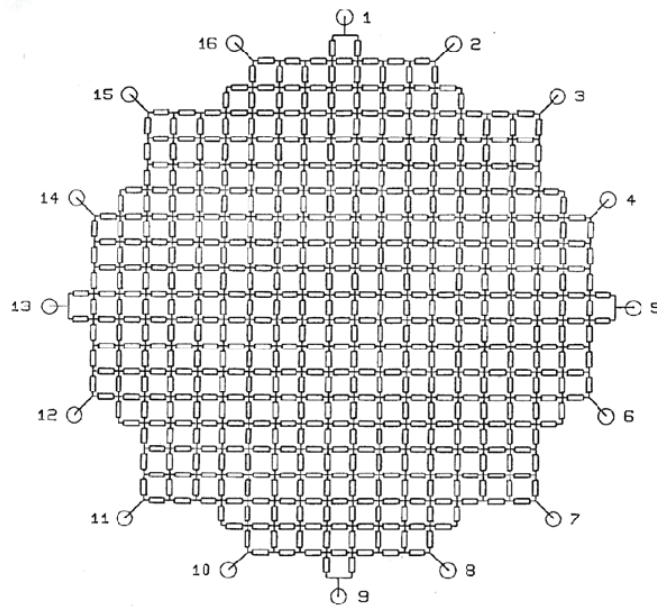


Figure 1. Shape of the CARDIFF EIT PHANTOM (v1.0 1991) used to characterize our system [3].

4. Discussion

The figures defined (SER, NER, RER) are suitable to characterize and compare EIT systems of (almost) any topology. However, to make valuable comparisons some agreement must be done on the measurement conditions, especially on the test object.

The shape and composition of the test object does have an impact not only on the calculation of SER, where the availability of a well known test object is required and its influence is obvious, but also on the computation of RER and NER. The shape and values of the test object will set the dynamic range of the measurements, thus setting a limit for the maximum achievable NER and RER. Using a test object consisting on a single resistor connected to all channels will produce the best results. This can be acceptable for comparison purposes but values obtained can be far from what is expectable in a real application. On the other hand, using a test object very tailored to an application can benefit some systems in front of others.

Using fixed or adaptive gain profiles is a common practice in EIT. However, the combination of gain profiles and a particular test object may bias the estimation of NER. For that reason using fixed gains and a “generic” test object produces values better suited for comparison.

References

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